

AD-A153 929

STRUCTURE-PROPERTY RELATIONSHIPS IN POLYMERIC MATRIX
MATERIALS(U) PRINCETON UNIV NJ DEPT OF CHEMICAL
ENGINEERING J K GILLHAM 15 APR 85 TR-27

1/1

UNCLASSIFIED

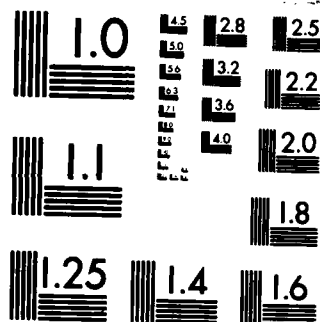
N00014-76-C-0200

F/G 11/4

NL



		END
		FORMED
		ONE



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A153 929

OFFICE OF NAVAL RESEARCH
Contract # N00014-76-C-0200

FINAL TECHNICAL REPORT
TECHNICAL REPORT NUMBER 27

Structure-Property Relationships
in Polymeric Matrix Materials

J. K. Gillham
Polymer Materials Program
Department of Chemical Engineering
Princeton University
Princeton, New Jersey 08544

August 1, 1975 - January 31, 1984

April 1985

DTIC
ELECTE
MAY 20 1985
S A D

Reproduction in whole or part is permitted for any purpose of the United States Government.

Approved for public release; distribution unlimited.

DTIC FILE COPY

85 4 20 000

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 27	2. GOVT ACCESSION NO. AD A15 3 929	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Structure-Property Relationships in Polymeric Matrix Materials		5. TYPE OF REPORT & PERIOD COVERED FINAL, 1975-1984
7. AUTHOR(s) J. K. Gillham		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Polymer Materials Program, Department of Chemical Engineering, Princeton University, Princeton, New Jersey 08544		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-0200
11. CONTROLLING OFFICE NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE April 15, 1985
		13. NUMBER OF PAGES 9
		15. SECURITY CLASS. (of this report) unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for Public Release, Distribution Unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Tsub II		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Cure, Epoxies, Torsion Pendulum), Torsional Braid Analysis Transition, Pyrolysis.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The main results of the research program are summarized in terms of: I) development of a time-temperature-transformation (TTT) cure diagram for thermosetting systems; II) automation of a torsion pendulum using digital computers; III) characterization of novel polymers, composites and transitions, and IV) development and application of a pyrolysis system for characterizing the thermal degradation mechanisms of polymers. Originator supplied Keywords include:		

ACCOMPLISHMENTS

I. The principal accomplishment is the evolution of a generalized time-temperature-transformation (TTT) cure diagram for thermosetting systems which permits an understanding of the cure behavior, properties, and degradation of thermosetting systems.

Introduction

Research in this laboratory has shown that a time-temperature-transformation diagram (analogous to the TTT diagrams that have been employed for many years in metallurgical processing) may be used to provide an intellectual framework for understanding and comparing the cure and physical properties of thermosetting systems (1,12,15,18,22,25,26). Isothermal TTT diagrams such as that shown in Figure 1 can be obtained by measuring the times to events which occur during isothermal cure versus temperature (T_{cure}). The events include phase-separation (for example, in rubber-modified systems -- not shown in Figure 1), gelation, vitrification, and devitrification. Gelation is synonymous with the incipient formation of an infinite network. Vitrification occurs when the glass transition rises through the isothermal temperature of cure. Devitrification occurs when the glass transition temperature decreases through the isothermal temperature. The diagram displays the distinct states encountered due to chemical reactions. These states include liquid, gelled rubber, ungelled glass, gelled glass, and char. The diagram also displays the critical temperature T_{go} , $g_{\text{el}}T_g$, and T_{go} which are, respectively, the glass transition temperature of the fully cured system, the temperature at which the times to gelation and to vitrification are the same, and the glass transition temperature of the unreacted reactants.

The TTT diagram shown in Figure 1 can be obtained conveniently using a technique (TBA) in which a resin-impregnated glass braid is the specimen in a torsion pendulum (1,6,12,15,23,24,25). Use of the composite specimen permits monitoring of the changes from liquid to rubber to glass, and to devitrification, which can occur on cure. Relationships between cure and properties (e.g., transitions) can be obtained from temperature scans of the cured specimens.

Discussion

Much of the behavior of thermosetting materials can be understood immediately in terms of the TTT diagram (Figure 1) through the influence of the gelation, vitrification, and devitrification events on properties: gelation limits macroscopic flow, and limits growth of a dispersed phase (as in rubber-modified systems); vitrification limits chemical conversion; devitrification marks the limit in time due to degradation for the material to support a load. Thus (in listed form):

- a) The ungelled glassy state is the basis of commercial molding and "prepreg" materials (21) since, on heating, the ungelled material will flow before gelling.
- b) Temperature $g_{\text{el}}T_g$ is a critical temperature in determining the upper



Availability Codes	
Avail and/or	Special
Dist	
A1	

temperature for storing reactive materials to avoid gelation.

c) The morphology developed in a two-phase system (e.g., those in which rubber-rich domains precipitate as a dispersed phase) on isothermal cure depends on the gelation temperature. The reaction temperature determines the competition between thermodynamics and kinetic (transport) factors. For optimum mechanical properties, a two-phase system will be cured at one temperature to control the morphology, and subsequently cured above $T_{g\infty}$ to complete the reactions of the matrix (19,20).

d) Shrinkage stresses due to cure begin to develop at gelation. There is a need to develop polymerization systems involving low shrinkage on cure.

e) Isothermal cure at temperature T_{cure} below $T_{g\infty}$ will (in principle) lead to $T_g = T_{cure}$. There is a need to develop mechanisms of cure which yield $T_g \gg T_{cure}$.

f) Complete cure is obtained (in principle) only by curing above $T_{g\infty}$. Correlations between macroscopic behavior and molecular structure will then result only after curing above $T_{g\infty}$.

g) For high $T_{g\infty}$ systems there is a competition between cure and degradation.

h) The limiting viscosity in the fluid state is controlled by gelation above temperature $g_{el}T_g$, and by vitrification below temperature $g_{el}T_g$. At gelation the weight average molecular weight and zero shear rate viscosity become infinite. Viscosity in the vicinity of vitrification is described by the Williams-Landel-Ferry equation.

i) Isothermal reactions proceed slowly after vitrification. Below temperature $g_{el}T_g$ this leads eventually to gelation. At high temperatures this leads eventually to degradation. Degradation can result in devitrification as the glass transition temperature decreases through the isothermal temperature due to decrease in crosslinking, or formation of low molecular weight plasticizing material. Degradation can also result in re-vitrification (e.g., char formation) as the glass transition rises through the isothermal temperature due to increase in crosslinking or volatilization of low molecular weight plasticizing material.

j) The times to gelation and to vitrification each can be computed from the reaction mechanism (or the reaction rate dependence on the concentrations of the reactants) and the extent of reaction at gelation (which is constant according to Flory's theory of gelation) and the extent of reaction at vitrification, respectively. Since vitrification occurs when the glass transition temperature rises to the temperature of cure, computation of the time to vitrify involves knowledge of the relationship between T_g and conversion.

The following is an outline for computation of the times to gelation and to vitrification. The overall reaction rate is a function of the temperature (T), extent of reaction (X), reaction mechanism $f(X)$, and local microviscosity (η_L) which in turn is a function of the molecular weight and temperature.

$$\frac{dX}{dt} = A \exp(-E_A/RT) f(X) f(\eta_L) \quad (I)$$

Analysis of an epoxy system showed that diffusion influenced the reaction rate only at vitrification (25). The general kinetic equation describing the reaction is then

$$\frac{dX}{dt} = A \exp(-E_A/RT) f(X). \quad (II)$$

The time to reach gelation

$$t_{gel}^* = \exp(Ar/T^*) \int_0^{X_{gel}} \frac{dX}{f(X)} \quad (III)$$

and the time to reach vitrification

$$t_{vit}^* = \exp(Ar/T^*) \int_0^{X_g(T^*)} \frac{dX}{f(X)} \quad (IV)$$

where $t_{gel}^* = At_{gel}$ and $t_{vit}^* = At_{vit}$ are the dimensionless times to reach gelation and vitrification, respectively; $T^* = T/T_{go}$ is a dimensionless temperature, and $Ar = E_A/RT_{go}$ is the Arrhenius number. X_{gel} and X_g are the extent of conversion of reactants at gelation and vitrification, respectively. The times to gelation and to vitrification can be computed using these equations (III and IV), knowledge of X_{gel} (for gelation) and a relationship between X_g and T_g (for vitrification), and the reaction kinetics. k) The vitrification curve is "S"-shaped. At temperatures immediately above T_{go} the time to vitrification passes through a maximum in consequence of the opposing influences of the temperature dependence of the viscosity and reaction rate constant. At higher temperatures the time to vitrification passes through a minimum in consequence of the opposing influences of the reaction rate constant and the decreasing concentration of reactive sites at vitrification as T_{go} is approached.

l) For epoxies the reactions become diffusion controlled in the vicinity of vitrification.

m) The reaction mechanism of a particular thermosetting system in principle can be deduced from the shape of the experimentally measured "S"-shaped vitrification curve.

n) Increasing cure time leads at the curing temperature to increasing conversion, T_g , crosslinking density, and density. Prior to vitrification the modulus at the curing temperature also increases. However in the glass state at room temperature, the corresponding modulus and density can

decrease whereas absorption of water can increase with increasing extent of cure (26).

TIME-TEMPERATURE-TRANSFORMATION (TTT) CURE DIAGRAM

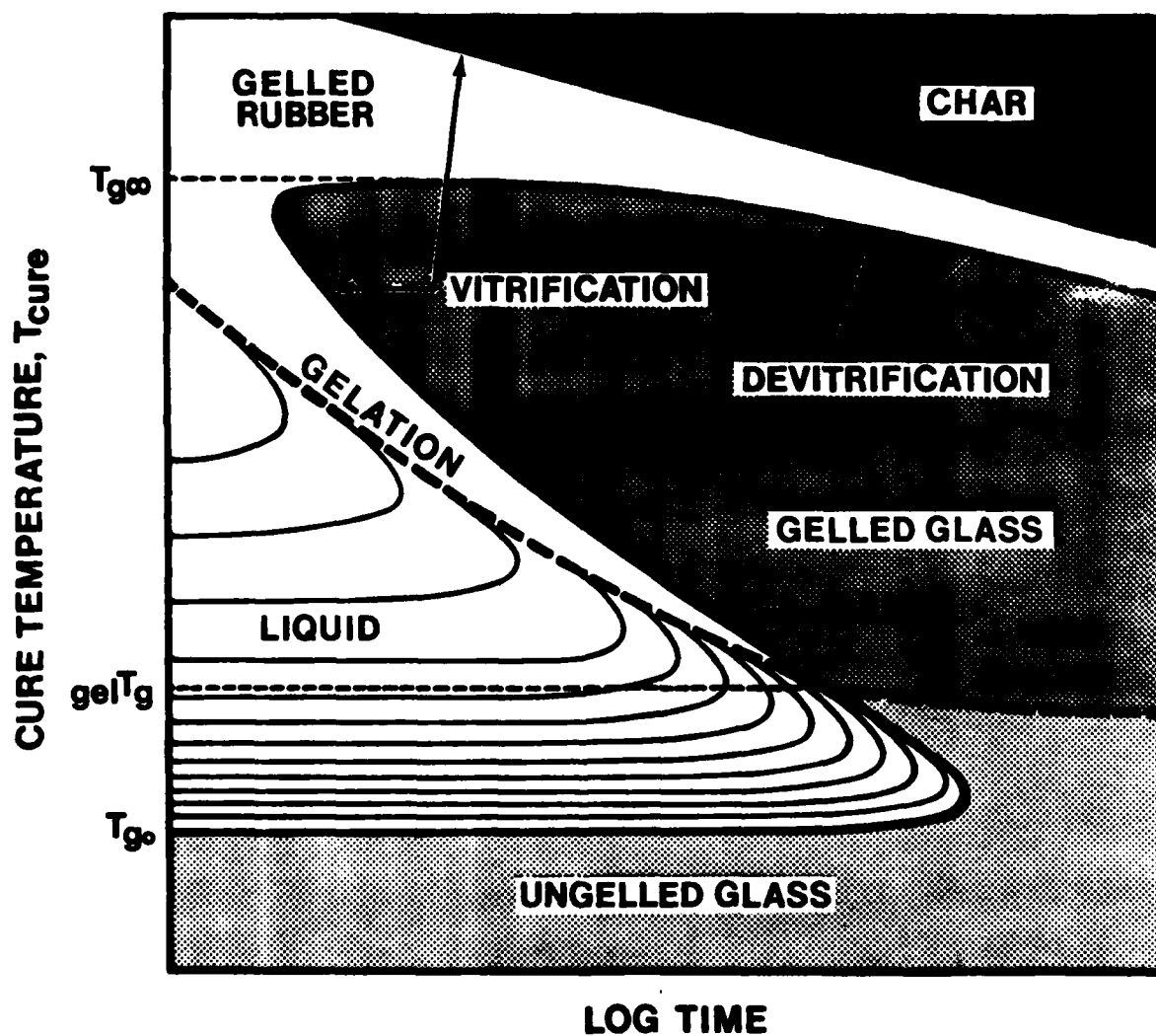


Figure 1

II. Much of the research has employed an adaptation of the freely oscillating torsion pendulum, "Torsional Braid Analysis (TBA)". Throughout this program the technique has been upgraded to include digital control and data reduction using hierarchical and desk-top computer systems (6,24).

III. The TBA technique (see II, above) has been central to developing the TTT cure diagram using epoxies (see I, above). It has also been used to characterize novel polymers such as bibenzoxazoles (5), tactic polymethylmethacrylates (6), and polyimides (14). It has also been employed to characterize high performance composite systems such as prepreps (21) and coated optical fibers (23). The technique was applied to difficult-to-investigate region above T_g of amorphous polymers where a relaxation, the T_{β} "transition", was investigated using homopolymers (2); blends of homopolymers (3), and block copolymers (13) of styrene.

IV. A new technique for investigating the thermal degradation of polymers was developed (4,7,8,10,16). The system uses a pyrolyzer in series with a thermal conductivity cell, a mass chromatograph, and an on-the-fly infrared spectrometer. The thermal conductivity cell gives the flexibility for selective trapping of volatile decomposition products, and also provides data that are complementary to thermogravimetric and differential thermal analyses. The mass chromatograph is composed of two gas chromatographs that are run parallel from a common injection port. Each chromatograph uses a different carrier gas and is equipped with a gas density detector. The instrument simplifies identification of mixtures of unknowns indirectly providing molecular weights, absolute quantities, and gas chromatographic retention times of the constituents. In this respect, the system is analogous to pyrolysis-gas chromatography-mass spectrometry. The infrared spectra together with the mass numbers provide a basis for assignment of molecular structure. The technique was used to investigate the degradation mechanism of polyolefins (7), polysulfones and polystyrene (8), and the influence of cis/trans ratio of 1,4-polybutadienes.

ONR TECHNICAL REPORTS (TR)/PUBLICATIONS

- TR#1 J. K. Gillham, Characterization of Thermosetting Materials by Torsional Braid Analysis. Polymer Engineering and Science, Vol. 16, No. 5, 353-356 (1976). AD No. A018338.
- TR#2 S. J. Stadnicki, J. K. Gillham and R. F. Boyer, The T_{gg} ($> T_g$) Transition of Atactic Polystyrene. Journal of Applied Polymer Science, Vol. 20, No. 5, 1245-1275 (1976). AD No. A021444.
- TR#3 C. A. Glandt, H. K. Toh, J. K. Gillham and R. F. Boyer, Effect of Dispersity on the T_{gg} ($> T_g$) Transition in Polystyrene. Journal of Applied Polymer Science, Vol. 20, No. 5, 1277-1288 (1976). AD No. A021443. Also *ibid*, Vol. 20, No. 7, 2009 (1976).
- TR#4 E. Kiran and J. K. Gillham, Pyrolysis-Molecular Weight Chromatography-Vapor Phase Infrared Spectrophotometry: A New On-Line System for Analysis of Polymers. I. Instrumentation. Journal of Applied Polymer Science, Vol. 20, No. 3, 931-947 (1976). AD No. A023780.
- TR#5 C. K. Schoff and J. K. Gillham, Structure-Property Relationships in Bibenzoxazole Polymers Containing Fluorocarbon Linkages. Journal of Applied Polymer Science, Vol. 20, No. 7, 1875-1884 (1976). AD No. A023822.
- TR#6 S. J. Stadnicki, J. K. Gillham and Y. Hazony, Low Frequency Thermomechanical Spectrometry of Polymeric Materials: Tactic Polymethylmethacrylates. Journal of Applied Polymer Science, Vol. 21, No. 2, 401-424 (1977). AD No. A026113.
- TR#7 E. Kiran and J. K. Gillham, Pyrolysis-Molecular Weight Chromatography: A New On-Line System for Analysis of Polymers. II. Thermal Decomposition of Polyolefins: Polyethylene, Polypropylene, Polyisobutylene. Journal of Applied Polymer Science, Vol. 20, No. 8, 2045-2068 (1976). AD No. A030996.
- TR#8 E. Kiran, J. K. Gillham and E. Gipstein, Pyrolysis-Molecular Weight Chromatography-Vapor Phase Infrared Spectrophotometry: An On-Line System for Analysis of Polymers. III. Thermal Decomposition of Polysulfones and Polystyrene. Journal of Applied Polymer Science, Vol. 21, No. 5, 1159-1176 (1977). AD No. A027166.
- TR#9 J. A. Benci, J. K. Gillham and R. F. Boyer, Investigation of the T_{gg} ($> T_g$) Transition in Polystyrene by Torsional Braid Analysis. Polymer Engineering and Science, Vol. 16, No. 5, 357-360 (1976). AD No. A027108.
- TR#10 S. Tamura and J. K. Gillham, Pyrolysis-Molecular Weight Chromatography-Vapor Phase Infrared Spectrophotometry: An On-line

System for Analysis of Polymers. IV. Influence of Cis/Trans Ratio on the Thermal Decomposition of 1,4-Polybutadienes. Journal of Applied Polymer Science, Vol. 22, No. 7, 1867-1884 (1978). AD No. A040557.

- TR#11 J. K. Gillham and R. F. Boyer, The $T_{\beta\beta}$ Relaxation of Polystyrene. Journal of Macromolecular Science, Physics, B13(3), 497-535 (1977). AD No. A040558.
- TR#12 C. A. Glandt, J. K. Gillham and C. A. McPherson, Characterization of Thermosetting Epoxy Systems Using a Torsional Pendulum. In Chemistry and Properties of Crosslinked Polymers, (Ed., S. S. Labana), Academic Press, New York. pp 491-520 (1977). AD No. A045886.
- TR#13 J. K. Gillham and R. F. Boyer, Investigation of the $T_{\beta\beta}$ ($> T_g$) Relaxation in Homopolymers and Block Copolymers of Styrene by Torsional Braid Analysis. AD No. A048455.
- TR#14 Y. Ozari, R. H. Chow and J. K. Gillham, A Water-Sensitive Thermomechanical Transition in a Polyimide. Journal of Applied Polymer Science, Vol. 23, No. 4, 1189-1201 (1979).
- TR#15 J. K. Gillham, Formation and Properties of Network Polymeric Materials. Polymer Engineering and Science, Vol. 19, No. 10, 676-682 (1979). AD No. A051451.
- TR#16 E. Kiran and J. K. Gillham, Pyrolysis-Molecular Weight Chromatography-Vapor Phase Infrared Spectrophotometry: An On-line System for Analysis of Polymers. In Developments in Polymer Degradation-2 (Ed. N. Grassie), Applied Science Publishers, Ltd., London, 1-33 (1979). AD No. A069500.
- TR#17 J. K. Gillham, Investigation of the $T_{\beta\beta}$ ($> T_g$) Relaxation in Homopolymers and Block Copolymers of Styrene by Torsional Braid Analysis. Polymer Engineering and Science, Vol. 19, No. 10, 749-755 (1979). AD No. A072075.
- TR#18 J. K. Gillham, The Time-Temperature-Transformation (TTT) State Diagram and Cure. In the Role of the Polymeric Matrix in the Processing and Structural Properties of Composite Materials (Ed. J. C. Seferis and L. Nicolais), Plenum Press, New York, 127-145 (1983). AD No. A073007.
- TR#19 L. T. Manzione, J. K. Gillham and C. A. McPherson, Rubber-Modified Epoxies: Transitions and Morphology. Journal of Applied Polymer Science, Vol. 26, 889-905 (1981). AD No. A090175.
- TR#20 L. T. Manzione, J. K. Gillham and C. A. McPherson, Rubber-Modified Epoxies: Morphology and Mechanical Properties. Journal of Applied Polymer Science, Vol. 26, 907-919 (1981). AD No. A090122.
- TR#21 N. S. Schneider and J. K. Gillham, TBA Studies of Prepreg Curing Behavior. Polymer Composites, Vol. 1, 97-102 (1980). AD No. A092780.

- TR#22 J. K. Gillham, The Time-Temperature-Transformation (TTT) State Diagram and Its Role in Determining Structure/Property Relationships in Thermosetting Systems. In Structure/Property Relationships of Polymeric Solids (Ed., A. Hiltner), Plenum Press, New York, pp. 215-225 (1983). AD No. A096127.
- TR#23 L. T. Manzione, J. K. Gillham, C. F. Tu and U. C. Paek, Characterization of Polymer-Coated Optical Fibers Using a Torsion Pendulum. Journal of Applied Polymer Science, Vol. 27, 1301-1311 (1982). AD No. AD A111150
- TR#24 J. B. Enns and J. K. Gillham, Automated Torsion Pendulum: Control and Data Collection/Reduction Using a Desktop Computer. Computer Applications in Coatings and Plastics (Ed., T. Provder), American Chemical Society, Symposium Series, No. 197, 329-352 (1982). AD No. 113038.
- TR#25 J. B. Enns and J. K. Gillham, Torsional Braid Analysis (TBA): Time-Temperature-Transformation (TTT) Cure Diagrams of Thermosetting Epoxy/Amine Systems. In Polymer Characterization: Spectroscopic, Chromatographic and Physical Instrumental Methods (Ed., C. D. Craver), American Chemical Society, Advances in Chemistry Series, No. 203, 27-63 (1983). AD No. A119836.
- TR#26 J. B. Enns and J. K. Gillham, Effect of the Extent of Cure on the Modulus, Glass Transition, Water Absorption, and Density of an Amine Cured Epoxy. Journal of Applied Polymer Science, Vol. 28, 2831-2846 (1983). AD No. A127090.

PERSONNEL

J. B. Enns, graduate student
C. A. Glandt, graduate student
E. Kiran, graduate student
L. T. Manzione, graduate student
S. J. Stadnicki, graduate student
Y. Ozari, post-doctoral student
S. Tamura, post-doctoral student
H. K. Toh, post-doctoral student
J. K. Gillham, principal investigator

AWARDS

- 1978 - American Chemical Society Award in the Chemistry of Plastics & Coatings (Borden Award).
- 1978 - North American Thermal Analysis Society Award in Thermal Analysis (Mettler Award)
- 1980 - American Chemical Society, Division of Organic Coatings and Plastics Chemistry; Best Technical Paper of Year (Doolittle Award)
- 1983 - Federation of Coatings Technologies; Best Technical Paper of Year (1st Prize Roan Award Competition)

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	<u>No. Copies</u>		<u>No. Copies</u>
Office of Naval Research Attn: Code 413 800 North Quincy Street Arlington, Virginia 22217	2	Naval Ocean Systems Center Attn: Mr. Joe McCartney San Diego, California 92152	1
ONR Pasadena Detachment Attn: Dr. R. J. Marcus 1030 East Green Street Pasadena, California 91106	1	Naval Weapons Center Attn: Dr. A. B. Amster, Chemistry Division China Lake, California 93555	1
Commander, Naval Air Systems Command Attn: Code 310C (H. Rosenwasser) Department of the Navy Washington, D.C. 20360	1	Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko Port Hueneme, California 93401	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12	Dean William Tolles Naval Postgraduate School Monterey, California 93940	1
Dr. Fred Saalfeld Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375	1	Scientific Advisor Commandant of the Marine Corps (Code RD-1) Washington, D.C. 20380	1
U.S. Army Research Office Attn: CRD-AA-IP P. O. Box 12211 Research Triangle Park, N.C. 27709	1	Naval Ship Research and Development Center Attn: Dr. G. Bosmajian, Applied Chemistry Division Annapolis, Maryland 21401	1
Mr. Vincent Schaper DTNSRDC Code 2803 Annapolis, Maryland 21402	1	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1	Mr. A. M. Anzalone Administrative Librarian PLASTEC/ARRADCOM Bldg 3401 Dover, New Jersey 07801	1

TECHNICAL REPORT DISTRIBUTION LIST, 356A

	<u>No. Copies</u>		<u>No. Copies</u>
Dr. M. Broadhurst Bulk Properties Section National Bureau of Standards U. S. Department of Commerce Washington, D.C. 20234	2	Dr. K. D. Pae Department of Mechanics and Materials Science Rutgers University New Brunswick, New Jersey 08903	1
Naval Surface Weapons Center Attn: Dr. J. M. Augl, Dr. B. Hartman White Oak Silver Spring, Maryland 20910	1	NASA-Lewis Research Center Attn: Dr. T. T. Serofini, MS-49-1 2100 Brookpark Road Cleveland, Ohio 44135	1
Dr. G. Goodman Globe Union Incorporated 5757 North Green Bay Avenue Milwaukee, Wisconsin 53201	1	Dr. Charles H. Sherman Code TD 121 Naval Underwater Systems Center New London, Connecticut 06320	1
Professor Hatsuo Ishida Department of Macromolecular Science Case-Western Reserve University Cleveland, Ohio 44106	1	Dr. William Risen Department of Chemistry Brown University Providence, Rhode Island 02191	1
Dr. David Soong Department of Chemical Engineering University of California Berkeley, California 94720	1	Mr. Robert W. Jones Advanced Projects Manager Hughes Aircraft Company Mail Station D 132 Culver City, California 90230	1
Dr. Curtis W. Frank Department of Chemical Engineering Stanford University Stanford, California 94035	1	Dr. C. Giori IIT Research Institute 10 West 35 Street Chicago, Illinois 60616	1
Picatinny Arsenal Attn: A. M. Anzalone, Building 3401 SMUPA-FR-M-D Dover, New Jersey 07801	1	Dr. R. S. Roe Department of Materials Science and Metallurgical Engineering University of Cincinnati Cincinnati, Ohio 45221	1
Dr. J. K. Gillham Department of Chemistry Princeton University Princeton, New Jersey 08540	1	Dr. Robert E. Cohen Chemical Engineering Department Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1
Dr. E. Baer Department of Macromolecular Science Case Western Reserve University Cleveland, Ohio 44106	1	Dr. T. P. Conlon, Jr., Code 3622 Sandia Laboratories Sandia Corporation Albuquerque, New Mexico	1

TECHNICAL REPORT DISTRIBUTION LIST, 356A

	<u>No. Copies</u>		<u>No. Copies</u>
Dr. Martin Kaufman Code 38506 Naval Weapons Center China Lake, California 93555	1	Professor C. S. Paik Sung Department of Materials Sciences and Engineering Room 8-109 Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1
Professor S. Senturia Department of Electrical Engineering Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1	Professor Brian Newman Department of Mechanics and Materials Science Rutgers, The State University Piscataway, New Jersey 08854	1
Dr. T. J. Reinhart, Jr., Chief Composite and Fibrous Materials Branch Nonmetallic Materials Division Department of the Air Force Air Force Materials Laboratory (AFSC) Wright-Patterson AFB, Ohio 45433	1	Dr. John Lundberg School of Textile Engineering Georgia Institute of Technology Atlanta, Georgia 30332	1
Dr. J. Lando Department of Macromolecular Science Case Western Reserve University Cleveland, Ohio 44106	1		
Dr. J. White Chemical and Metallurgical Engineering University of Tennessee Knoxville, Tennessee 37916	1		
Dr. J. A. Manson Materials Research Center Lehigh University Bethlehem, Pennsylvania 18015	1		
Dr. R. F. Helmreich Contract RD&E Dow Chemical Co. Midland, Michigan 48640	1		
Dr. R. S. Porter Department of Polymer Science and Engineering University of Massachusetts Amherst, Massachusetts 01002	1		
Professor Garth Wilkes Department of Chemical Engineering Virginia Polytechnic Institute and State University Blacksburg, Virginia 24061	1		

END

FILMED

6-85

DTIC